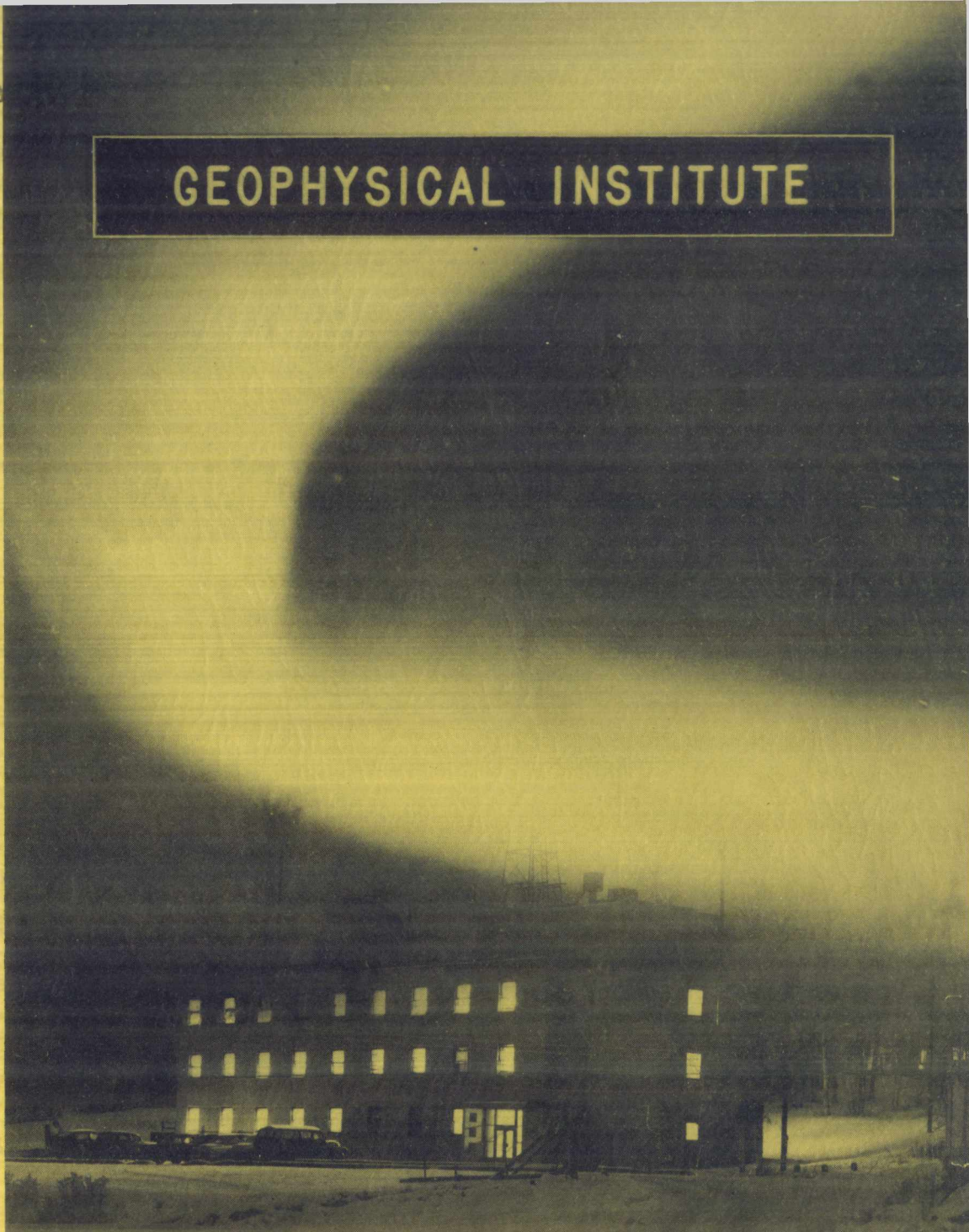


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THE HEIGHT OF F-LAYER IRREGULARITIES IN THE ARCTIC IONOSPHERE

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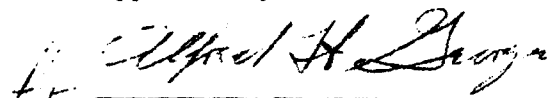
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Date Submitted:

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Approved by:



C. T. Elvey, Director
Geophysical Institute

THE HEIGHT OF F-LAYER IRREGULARITIES IN THE ARCTIC IONOSPHERE

ABSTRACT

Results and interpretations of oblique incidence soundings of the arctic ionosphere are presented. Anomalous echoes are found to be prevalent in high latitudes in contrast to lower latitudes where 2F groundscatter predominates. One of the echoes seen regularly at College, Alaska has been identified as direct F-layer (1F) backscatter. The observations of the 1F echo provide direct evidence of the presence of irregularities in the F-layer between heights of 350 and 600 km. The 1F echoes are recorded regularly at night and occasionally during the day in disturbed periods. They appear to be associated with auroral ionization.

Simultaneous reception of 2F echoes from the north and the south indicates that at times the reflecting layer is tilted. Tilt-angles in the vicinity of 2 to 3 degrees are found. The 2F echoes from the north usually connect to the extraordinary branch of the vertical incidence trace while the 2F echoes from the south appear to connect to the ordinary branch.

The analysis of groundscattered (2F) echoes is extended from a plane to a spherical geometry, and it is shown that a geometrical extension of the plane earth theory is adequate. The observed range-frequency dependence differs only slightly from that predicted by the latter theory.

1. Introduction

The literature contains ample evidence of the existence of irregularities in the electron density distribution of the F-layer^{1,2,3}. It is also generally accepted that the presence of the earth's magnetic field causes the irregularities to assume an ellipsoidal shape with the major axis oriented parallel to the magnetic lines of force.

In the arctic ionosphere the field lines are nearly vertical, so the irregularities will tend to have their major axes oriented almost vertically. Irregularities of this nature will exhibit an aspect sensitivity with respect to the scattering of incident radio waves, and the preferred direction of scatter will be on a conical surface of revolution about the major axis of the ellipsoid; the vertex angle of the cone will be twice the complement of the angle of incidence⁴. For normally incident waves the preferred direction of scatter will therefore be in the plane normal to the major axis.

There is some controversy in the literature about the height to which F-layer irregularities may extend. It appears to be generally accepted that irregularities exist below 200 or perhaps 300 km, but some authors have expressed doubt about the presence of irregularities at greater heights³. The work described in this paper provides direct evidence that electron density irregularities exist at actual heights between 350 and 600 km, and furthermore, that they are a common phenomenon in the arctic ionosphere.

The observations were made with an ionospheric sounder swept in frequency through the range from 1 to 25 Mc/s with the radiation obliquely incident on the ionosphere. The results of the observations are presented in Section 2. A primitive model for direct backscatter from the F-layer is

discussed in Section 3. The analysis of 2F groundscatter echoes is extended from a plane to a spherical geometry in Section 4. F-layer tilts deduced from simultaneous soundings north and south are discussed in Section 5. We summarize the results of the investigation in Section 6.

Appendices 1 and 2 contain sample calculations illustrating the methods used to obtain the height of the F-layer irregularities and the half-thickness of the layer, as well as the layer tilt. The equipment is described in detail in Appendices 3 and 4.

2. Observations

The observations discussed in this paper were made with an ionospheric sounder which was swept in frequency over the range of 1 to 25 Mc/s. Once every 15 minutes the radiation was beamed obliquely north and south during a six-minute period as the equipment swept through the frequency band. The records were obtained by photographing the trace of an intensity modulated cathode ray tube. The sounder, a modified C4 ionospheric recorder, and the antenna characteristics are described in more detail in Appendices 3 and 4.

In addition to the oblique incidence observations, simultaneous vertical incidence ionograms, obtained with a C-3 sounder on a routine basis, were available.

Typical samples of the oblique incidence records, arranged in chronological order, are shown in Fig. 1. Labelled sketches of the same records are presented in Fig. 2.

Fig. 1a is an example of 1F and 2F echoes occurring simultaneously. Unfortunately the high receiver gain required for the observations caused the vertical incidence trace to be obscured. At that particular time, the

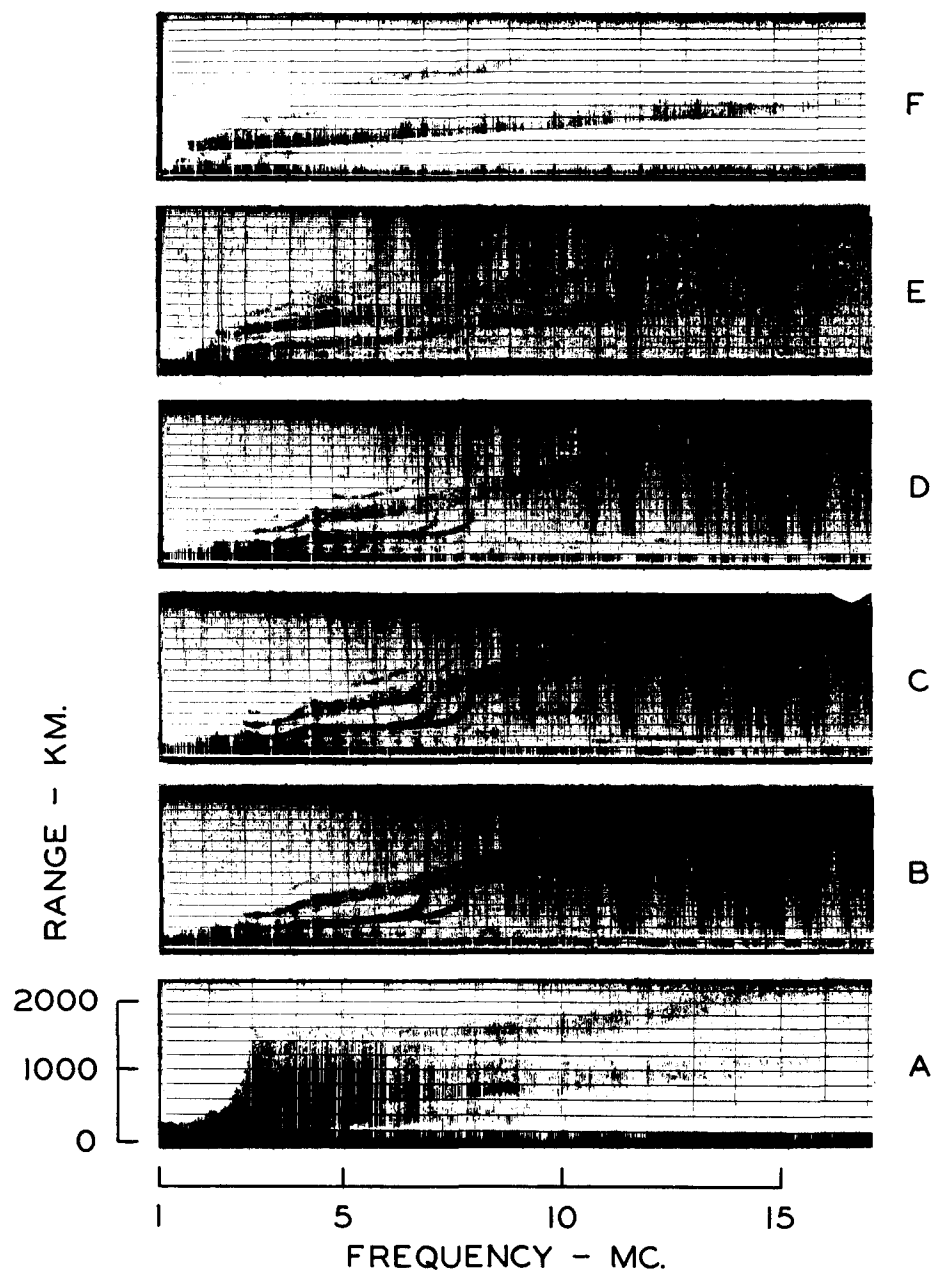


Fig. 1. Oblique incidence ionograms recorded at College, Alaska at the following times.

- A 0236 AST, April 16, 1958
- B 0506 AST, June 20, 1958
- C 0521 AST, June 20, 1958
- D 0551 AST, June 20, 1958
- E 0451 AST, August 14, 1958
- F 0121 AST, September 12, 1958

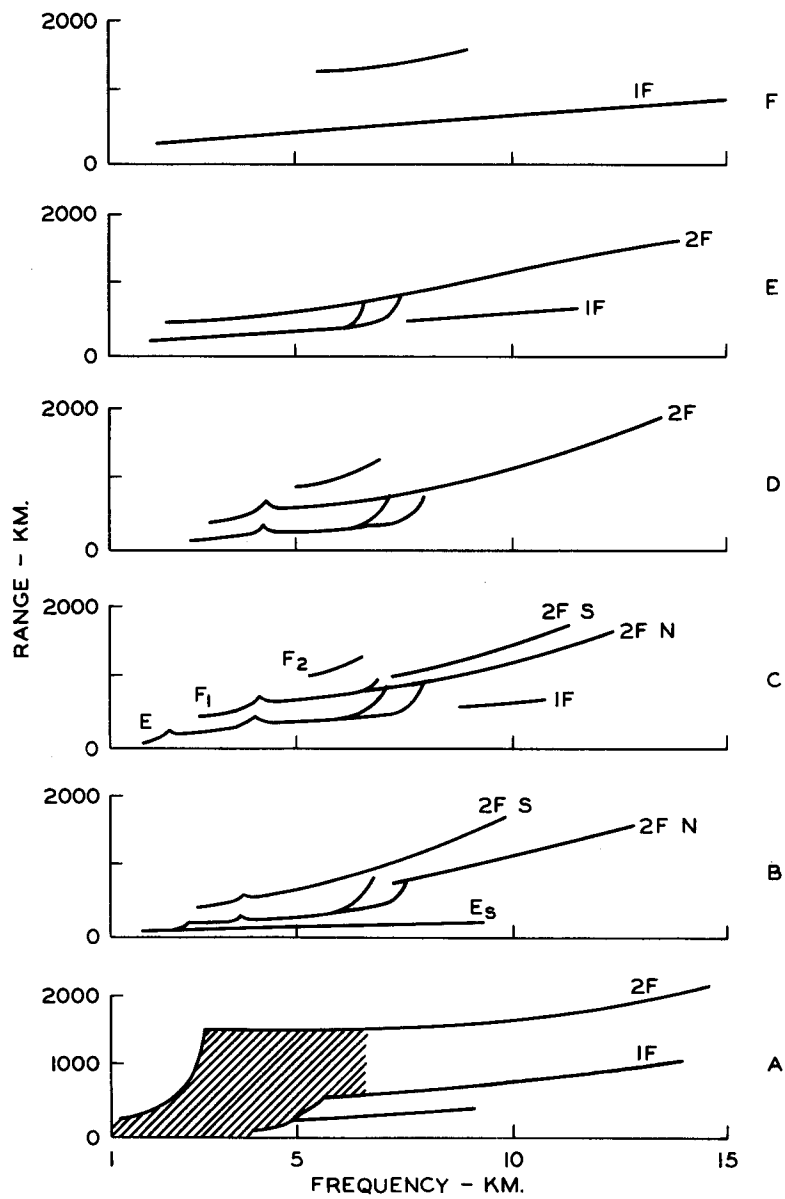


Fig. 2. Sketch of the records shown in Fig. 5. Areas marked E, F_1 , and F_2 contain vertical incidence echoes (multi-hop in some cases) from those regions. E_s is the sporadic E echo; 1F and 2F are the direct and ground scattered echoes, respectively. N or S indicates north or south.

C3 ionospheric recorder at College was not operating, and no corresponding clear vertical incidence record can be shown.

Fig. 1e is an excellent example of 1F and 2F echoes returned simultaneously. The extraordinary vertical incidence trace is fairly clear, and while the start of the 1F trace is obscured, the equivalent height at the tangent point is approximately 550 km, leading to an actual height in the neighborhood of 450 km. The method of calculation is described in Appendix 1.

Fig. 1f is the most common type of 1F echo that we observe. It is present at some time during nearly every night, and in disturbed periods it is seen occasionally in the day also. The vertical incidence sounder will generally show a spread-F record when this type of 1F echo is observed.

Fig. 1d contains a 2F echo that is tangent to the two-hop extraordinary cusp of the vertical incidence trace. The E, F₁, and F₂ layers are present as well as some sporadic E.

Figs. 1b and 1c were taken fifteen minutes apart. They contain a multitude of various vertical and oblique echoes; the E, E_s, F₁, and F₂ traces are clearly discernable. The 1F echo is weak but clear in Fig. 1c. It should be noted that the 2F echo from the north is tangent to the extraordinary cusp and the 2F from the south is tangent to the ordinary cusp of the vertical incidence trace. Fig. 1c shows this more clearly than Fig. 1b.

The receiver sensitivity is such that groundscatter echoes from the north are at best marginal. In an effort to get 2F echoes the terminations were removed from the transmitting and the receiving antennas, and subsequently simultaneous 2F echoes from the south and the north were occasionally observed.

3. Direct Backscatter from F-Layer Irregularities

In 1951 Peterson⁵ presented a simple theory using geometrical optics that explained the observed behaviour of HF backscatter from the ground propagated via the F-layer of the ionosphere. He showed that the path of minimum transit time for any given frequency leads to a time-focusing effect that tends to strongly enhance the leading edge of the backscattered echo.

This time-focusing effect is applicable to modes of propagation other than the groundscatter or 2F mode. Peterson calculated the path of minimum transit time by minimizing the time taken to reach the midpoint of the path and then applying symmetry arguments to obtain the whole path. The fact that the energy is scattered back from the ground is not a decisive factor in the theory, and it applies equally well to scatter from the midpoint.

With the above comments as a starting point the following primitive model is proposed. It is emphasized that the model represents the simplest possible and that ray theory is used exclusively. For a quantitative theory wave optics would be required, but because we are dealing with frequencies at or near the critical frequency, no wave solution to this scattering problem exists.

Consider that the ordinary F-layer has imbedded in it thin, vertical columns of additional ionization. If a radar reflection is to be obtained from such a column, the ray must be normal to the column, and hence horizontal. Any ray that is horizontal in the ionosphere is in the process of being refracted back to earth; thus only those frequencies that are returned to earth can give a radar reflection from the cylinders.

If there were no time-focusing effect in the ionosphere, the echo amplitude from any given cylinder would vary as the inverse distance, resulting in

a very broad echo. However, the least-time focusing enhances the leading edge of the echo just as for groundscatter, giving a comparatively narrow and well defined echo. To be consistent with the established notation, this will be called the 1F mode. Fig. 3 shows the geometry involved.

This model would produce echoes having precisely one-half the slope and range of the corresponding 2F echo if the vertical discontinuities were distributed over a large enough portion of the ionosphere.

Such echoes are seen, and an excellent example is Fig. 1e in which both the 1F and 2F echoes are present. The ratio of the ranges at any given frequency is very close to 2 below 13 megacycles, and above that it increases slightly. This increase is to be expected because of two factors: the tilt of the earth's magnetic field, and the finite angular width of the scattering polar diagram of the irregularities. Both factors cause the leading edge of the scattering point to be displaced slightly toward the observer from the geometrical midpoint of the path, and both become more important as the angle of incidence is increased.

The analysis of the 1F mode leads to the conclusion that the irregularities in the F-layer are distributed horizontally along a NS line over a considerable portion of the ionosphere. In Fig. 1f the maximum slant range is at least 1200 km; thus for an irregularity height of 500 km the actual NS extent of the irregularities exceeds 1000 km. Horizontal NS extents exceeding 1500 km have been observed using this method.

In many records the start of the 1F trace from the vertical incidence trace is missing, such as in Fig. 1e. This leads to the conclusion that the irregularities are in patches rather than distributed horizontally throughout the F-layer. For example in Fig. 1e the irregularities appear to be only at zenith angles exceeding 35° .

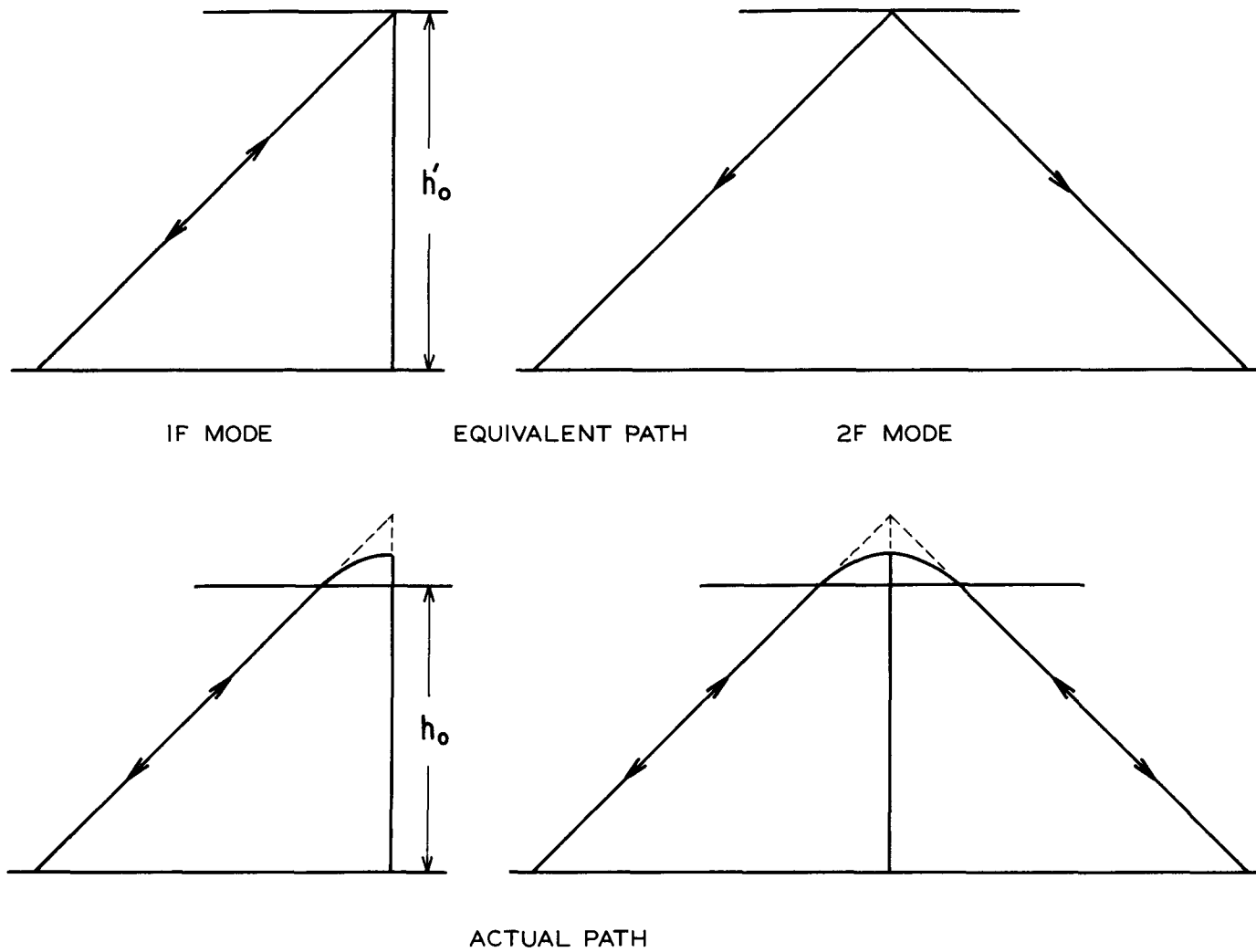


Fig. 3. The geometry for the 1F and the 2F modes of propagation.

The heights of the irregularities as derived from the 1F mode lie between 350 and 600 km for the data analyzed so far. A sample calculation of the actual height of the irregularities for Fig. 1e is shown in Appendix 1.

It must be noted, however, that the 1F mode yields information only about the irregularities that exist in the region where the earth's magnetic field lines and the least-time ray intersect at right angles. This region is just below the F-layer maximum; thus a statistical examination of the height distribution would yield no information other than the variation in height of the layer maximum.

The 1F echo appears for several hours nearly every night. One might conclude that because the irregularities occur so regularly at a relatively fixed height within the layer, their vertical distribution is probably much more general within the F-layer. Thus it appears reasonable that the irregularities usually extend vertically through much of the F-layer whenever they appear at its maximum.

Using the spread-F and radio star scintillation data from three temperate latitude stations, Briggs³ concluded that bands of irregularities existed in the ionosphere up to 300 km above the earth, and had horizontal geomagnetic NS extents up to 450 km. He suggested further that their geomagnetic EW extent was considerably greater, and that the bands were aligned roughly along the lines of constant geomagnetic latitude.

College is near the auroral zone maximum so the discrepancy between the numerical results is neither surprising nor contradictory. On the contrary one would certainly expect that most disturbances would be greater in the auroral zone than elsewhere. Another factor is that the F-layer maximum is higher in the Arctic than in the temperate ionosphere.

A few of the recorded 1F echoes were observed visually in order to obtain qualitative fading rate information. All of those observed exhibited the characteristic fast flutter of the auroral-type echo. It is therefore tempting to assume that the 1F echo is generally auroral in nature. It occurs during most nights and even during the day in disturbed periods, and appears to correlate closely with the occurrence of spread-F on the vertical incidence ionograms. At present we have insufficient data to make conclusive statements on these points, but the problem is under continued study.

Another characteristic of the 1F echo is that it usually branches off the extraordinary vertical incidence trace; also the 2F groundscatter from the north appears to branch off the extraordinary trace. Both of these items need further study however.

When the 1F echo is strong on the oblique incidence sounder, the vertical incidence sounder at College will generally show the start of the 1F trace as a spur off the knee of the extraordinary cusp. When this occurs, the values of h_o , f_c , and f_t can be scaled accurately, and the half-thickness of the layer can be calculated with greater precision than is possible with the data from the oblique incidence sounder alone, (see Section 4, Eq. 14). This is mainly due to the differences in sensitivity, pulse width, and sweep rate for the two equipments.

4. Geometrical Considerations

List of Symbols

s' = equivalent path length

r_o = radius of base of layer

y_m = half thickness of parabolic layer

h_o = distance from earth to base of layer

θ = angle of incidence at base of layer

s = $\sin \theta$

c = $\cos \theta$

f_c = vertical incidence critical frequency

f = transmitting frequency

f_t = tangent frequency for 1F (same as for 2F) echo to vertical incidence trace

ϕ = angle of linear tilt of plane layer

$$\rho = \frac{f}{f_c}$$

$$\rho_t = \frac{f}{f_t}$$

$$K = \left(\frac{h_o}{h_o + y_m} \right)^{\frac{1}{2}}$$

$$\beta = \left(1 - \frac{2h_o r_o - h_o^2}{r_o^2 c^2} \right)^{-\frac{1}{2}}$$

$$\gamma = \frac{y_m}{r_o}$$

List of Symbols (Cont'd.)

θ' = angle of incidence at apex of equivalent path

r'_0 = radius at apex of equivalent path

$C' = \cos \theta'$

$\beta' = \beta(r'_0, C')$

h'_0 = distance from earth to equivalent reflecting plane

In order that groundscattered radio waves propagated via the ionosphere can be used for short term predictions of point-to-point communications, the distance to the scattering area as a function of frequency must be known. Peterson⁵ showed by a ray theory analysis that for a plane, horizontally stratified, parabolic ionosphere the equivalent height of the ray for the minimum time of transit at oblique incidence is constant for all frequencies. The range-frequency dependence of such a model is easy to calculate, but unfortunately it does not fit the physical situation very well because of the earth's curvature.

Two methods can be used to obtain a better approximation. The first is to assume that the plane earth results hold for the spherical case, and the second is to obtain an approximate solution for the spherical case.

Extended plane earth method

The first method (the extended plane earth case) actually has two parts, depending on the assumptions made. The first case utilizes the following assumptions: (1) the path discussed is the equivalent path; (2) the radius r'_0 of the surface that reflects the least time path is constant; (3) the angle of incidence is measured between the path at its apex and the radius r'_0 ;

and (4) the secant law holds. Using these assumptions, one can either quickly calculate the range-frequency dependence or obtain it graphically⁶. The equivalent path length for the extended plane earth in case 1 is given by

$$s' = r'_0 C' \left(1 - \frac{1}{\beta'}\right) \quad (1)$$

The relation between the angle of incidence of the minimum time path and the transmitted frequency is retained and is given by

$$\rho = \frac{K}{C'} \quad (2)$$

The method described above does not take the layer thickness into account explicitly. Usually the angle of incidence is measured at the base of the layer rather than the apex of the path. As a second approximation, or case 2, we replace condition (3) above by: (3'), the angle of incidence is measured between the equivalent path and the radius r'_0 at the base of the layer; and retain the other assumptions. The results of this change are that Eq. 1 remains the same and the prime is removed from C' in Eq. 2.

The major disadvantages of the second method over the first are that more information about the ionosphere is required and that the angle of incidence must be determined by some means - for instance graphically.

Spherical earth method

An approximate geometrical optics solution has been worked out for the curved earth case for a spherical layer having a parabolic ion distribution. We use an approximation due to Försterling and Lassen⁷, referred to and applied by Kelso⁸. The effects of collisions and the earth's magnetic field

are neglected. The total path length is then given by⁹

$$s' = r_o c(1 - \frac{1}{\beta}) + \frac{y_m \rho}{2} \ln \frac{1 - \gamma s^2 \rho^2 + \rho c}{1 - \gamma s^2 \rho^2 - \rho c} \quad (3)$$

Using Peterson's method⁵ to find the path of minimum time as a function of the angle of incidence, one differentiates Eq. 3 with respect to θ , sets it equal to zero, and solves the resulting equation for ρ .

$$r_o (\beta - 1) - \frac{y_m \rho^2 - y_m}{(1 - \gamma s^2 \rho^2)^2 - \rho^2 c^2} \gamma \rho^4 (1 + c^2) = 0 \quad (4)$$

Eq. 4 is a bi-quadratic equation of the form of Eq. 5, and so it can be solved exactly by the quadratic formula.

$$x^4 - bx^2 + c = 0 \quad (5)$$

Thus

$$x^2 = \frac{b}{2} \left(1 - \sqrt{1 - \frac{4c}{b^2}} \right) \quad (6)$$

Now $4c \ll b^2$ so the radical can be expanded by the binomial series. If only the first two terms are retained, the result is precisely the same as if the x^4 term merely had been neglected in Eq. 4 namely,

$$x^2 = \frac{c}{b} \quad (7)$$

The Lagrange form of the Taylor series remainder was used for the above expansion. For the typical F-layer values of $y_m = 100$ km and $h_o = 400$ km, the error in ρ for all possible angles of incidence is less than 2%.

Substitution of the values of the coefficients from Eqs. 4 and 5 into Eq. 7 yields

$$\rho = (c^2 + 2\gamma s^2 + \frac{\gamma}{\beta - 1})^{-\frac{1}{2}} \quad (8)$$

Comparison of theory and experiment

The results for the two methods are as follows.

Spherical Case

$$s' = r_o c (1 - \frac{1}{\beta}) + \frac{y_m \rho}{2} \ln \frac{1 - \gamma s^2 \rho^2 + \rho c}{1 - \gamma s^2 \rho^2 - \rho c} \quad (9)$$

where

$$\rho = (c^2 + 2\gamma s^2 + \frac{\gamma}{\beta - 1})^{-\frac{1}{2}} \quad (10)$$

Extended Plane Cases

$$s' = r'_o c' (1 - \frac{1}{\beta'}) \quad (11)$$

$$\text{where I } \rho = \frac{K}{c'} \quad (12)$$

$$\text{or II } \rho = \frac{K}{c} \quad (13)$$

Fig. 4 shows the equivalent ranges resulting from Eqs. 9 and 10 (labeled spherical case), Eqs. 11 and 12 (labeled extended plane case 1) and Eqs. 11 and 13 (labeled extended plane case 2) plotted as functions of the normalized frequency along with the plane earth case as originally discussed by Peterson⁵. The agreement is sufficiently close to make the extended plane earth case 1 adequate for practical purposes.

In Fig. 5 experimental points, scaled from the 2F echo in Fig. 1d, are compared with curves plotted from Eqs. 11 and 12, and the agreement is good.

Kelso⁸ found that very little was gained in most cases by using a Chapman layer rather than a parabolic layer for the curved earth case. Hence for

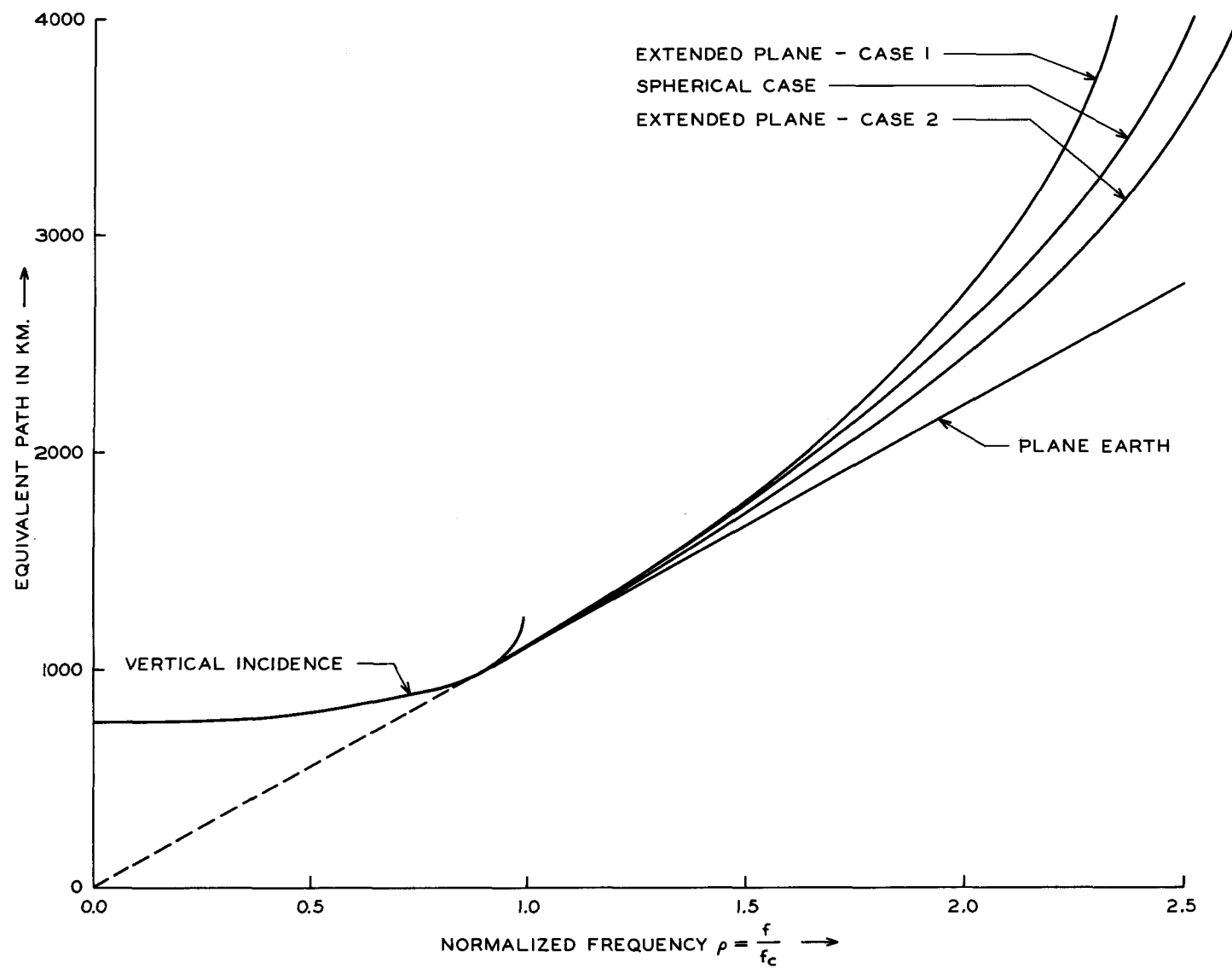


Fig. 4. The comparison of the theories on the range-frequency dependence of 2F backscatter.

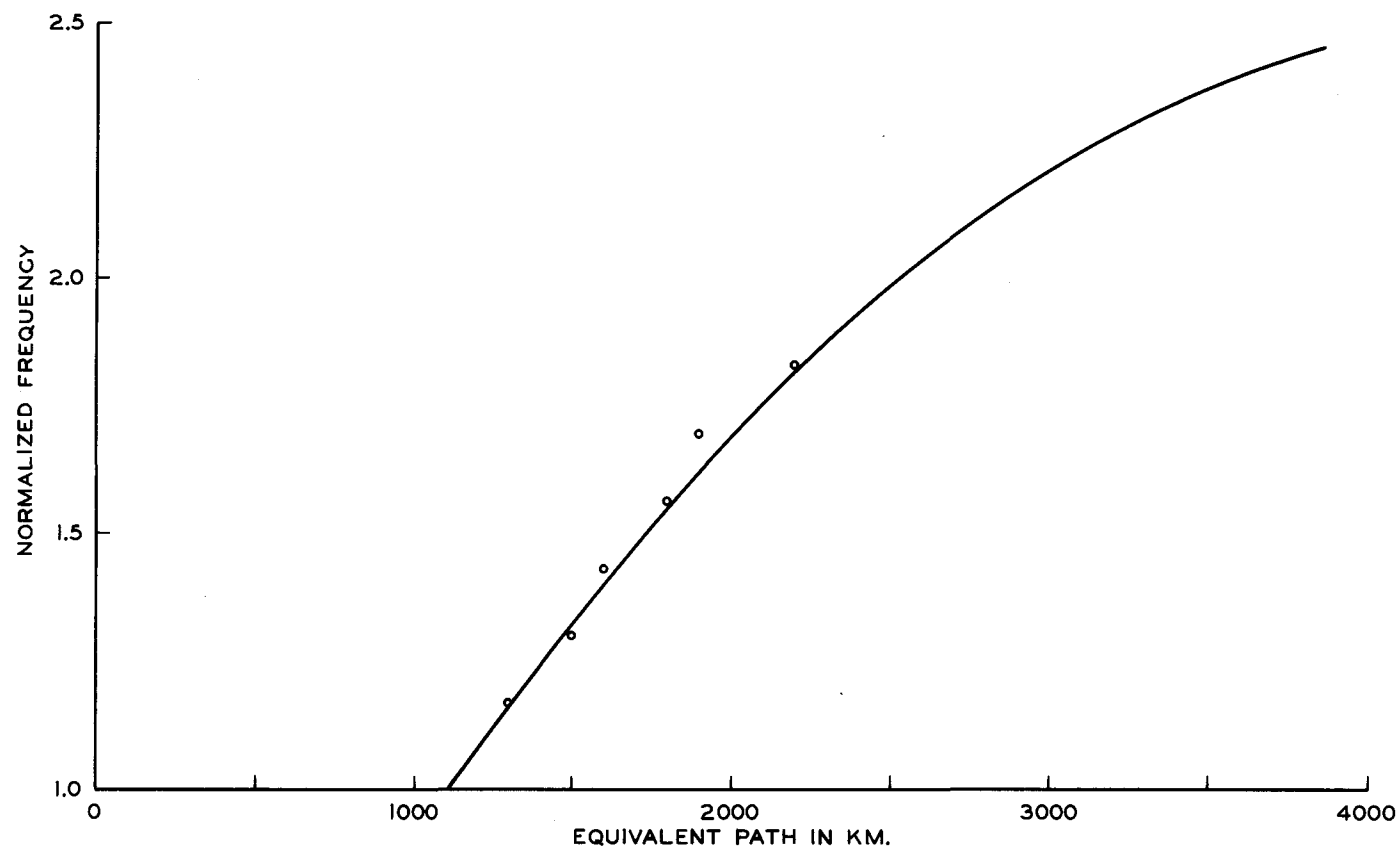


Fig. 5. The extended plane earth case 1 theory compared with the experimental data for 2F backscatter from Fig. 1D.

groundscatter and communications purposes in general, the extended plane earth theory is adequate even if non-parabolic layers are considered.

When the angle of incidence is zero in Eq. 8, the resulting frequency f_t is the frequency at which the 2F trace is tangent to the knee of the vertical incidence trace. This leads to a convenient means of calculating the half-thickness of the equivalent parabolic layer. One merely scales h_o , f_c , and f_t from the vertical incidence trace and uses Eq. 14.

$$y_m = h_o \frac{1 - K^2}{K^2} \quad (14)$$

Even though this is not the true half-thickness of the actual layer, it nevertheless reflects a physical property of the layer and provides a parameter that is useful for propagation predictions.

In Fig. 1c the half-thickness of the F_2 layer is $60 < y_m < 90$ kilometers. For greater precision the sweep would have to be expanded and the pulse width decreased.

5. Tilts Observed in the F-Layer

Let it be assumed that a tilt exists in the layer of reflection for a plane earth and a plane ionosphere as shown in Fig. 6. As a first approximation the equivalent height of the minimum time ray will be assumed to vary linearly, producing a tilt at an angle ϕ . Then an elementary calculation shows that the difference δ between the paths P_1 and P_2 for a given angle of incidence at the layer will be given by

$$\delta = \frac{2 h_o' S \sin 2\phi}{c^2 - \sin^2 \phi} \quad (15)$$

If ϕ is small, this reduces to

$$\delta = \frac{4 h_o \phi S}{c^2} \quad (16)$$

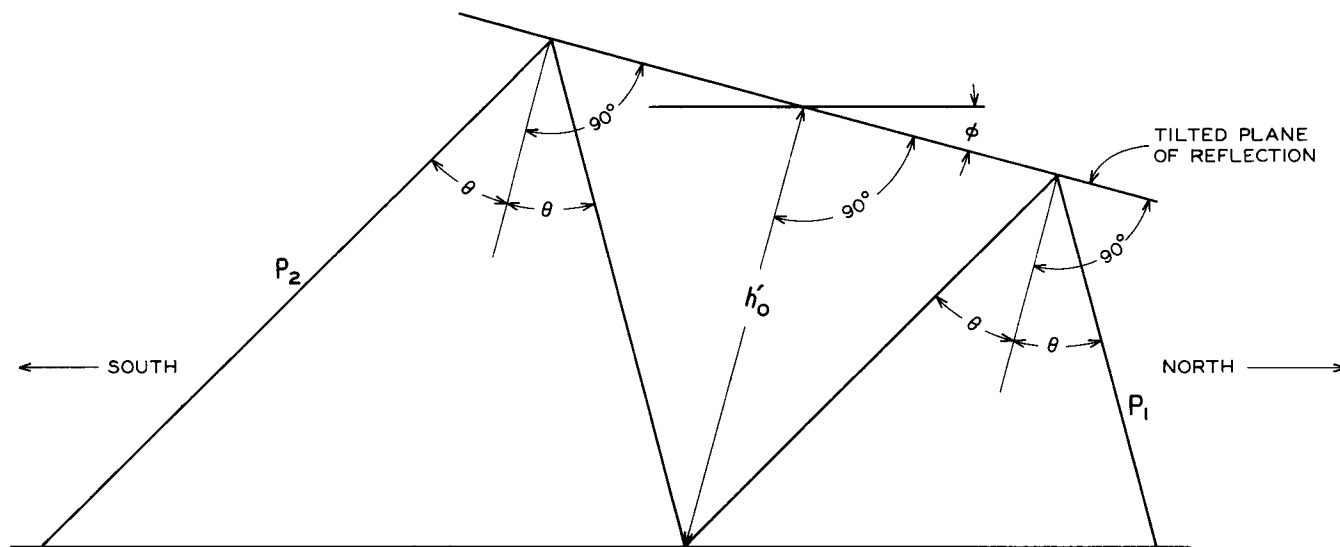


Fig. 6. The geometry for the tilted plane of reflection.

This can be solved easily for the angle ϕ , and after simplification, the final result is

$$\phi = \frac{\delta}{4h_0' \rho_t \sqrt{\rho_t^2 - 1}} \quad (17)$$

Using the data from Fig. 1c the angle of tilt is $1^\circ < \phi < 4^\circ$, which agrees with the values given by Stein^{10,11}. The computation is shown in Appendix 2.

6. Conclusions

The observed 1F echoes are explained by a simple model. They occur quite regularly during the night hours, and also occasionally during the day in disturbed periods.

The 1F echoes give direct evidence that F-layer irregularities exist from 350 to 600 km above the earth and sometimes extend 1500 km in a NS direction. At times the irregularities exist in patches.

The simultaneous reception of 2F echoes from the north and the south shows that layer tilts are possible and that they must be considered when making propagation predictions.

It is shown that for the analysis of backscatter records the plane earth theory is adequate if curvature is taken into account geometrically. The observed 2F echoes agree satisfactorily with the theory.

Both the 1F and the 2F echoes from the north usually branch off the extraordinary vertical incidence trace, while the 2F echo from the south branches off the ordinary trace. The last result is of preliminary nature, and requires substantiation by further observations.

Acknowledgements

The author wishes to thank Dr. Leif Owren for his invaluable assistance and criticism, and the US Air Force for supporting the research reported in this paper.

APPENDIX I

The method used for obtaining the height of the F-layer irregularities is illustrated in the following sample calculation. The record of Fig. 1e is used. The following values may be read off the record.

$$h_o = 350 \text{ km}$$

$$x^f_c = 8.0 \text{ Mc/s}$$

$$f_t = 7.3 \text{ Mc/s}$$

Hence $K^2 = 0.83$

Using Eq. 14 the half-thickness is given by

$$y_m = h_o \frac{1 - K^2}{K^2}$$

Thus the height of the irregularities is approximately 425 km.

Another method that is simpler to use is the useful relation from the Booker and Seaton method of analyzing $h'-f$ records¹²: for $\rho = 0.83$, the equivalent height equals the height of the layer maximum. The result is 450 km which agrees with the above calculation.

APPENDIX II

The record in Fig. 1b will be used to illustrate the computation of the layer tilt. The values read off the record are as follows:

$$h_o = 400 \text{ km}$$

$$o^f_c = 7.2 \text{ Mc/s}$$

$$o^f_t = 6.5 \text{ Mc/s} \quad \text{ORDINARY RAY}$$

So,

$$o^K = 0.90$$

$$x^f_c = 8.0 \text{ Mc/s}$$

$$x^f_t = 6.5 \text{ Mc/s} \quad \text{EXTRAORDINARY RAY}$$

So,

$$x^K = 0.90$$

For an angle of incidence of 26° we find the following from Fig. 1b.

$$\rho_t = 1.11 \quad o^f = 7.2 \text{ Mc/s} \quad h' = 1240 \text{ km}$$

$$\rho_t = 1.11 \quad x^f = 8.0 \text{ Mc/s} \quad h' = 1200 \text{ km}$$

$$\delta = 40 \text{ km}$$

and

$$\phi = 2.7^\circ$$

This value is probably within plus or minus one degree. The difficulty in reading the data precludes any better accuracy.

APPENDIX III

Equipment

The equipment used is a National Bureau of Standards Model C4 ionospheric recorder purchased for use under Contract AF 19(604)-1859. It has been modified in the following ways to obtain oblique incidence records.

1. Broadened 200 kilometer range marks are produced from the normal narrow 100 kilometer marks, for better recording with the increased sweep length.
2. The transmitter pulse width was increased from 100 to 600 microseconds.
3. An external third IF strip has been added to produce a 3 kilocycle bandwidth.
4. A squaring amplifier follows the added IF strip and contains an adjustable clipper that is adjusted to operate whenever the detected output from the third IF rises above an arbitrary average noise level. It clips at approximately the top of the "grass" level, making a weak echo record more prominently.

The equipment is licensed for 4 six-minute sweeps per hour, but because of the interference it causes to television reception in its vicinity, it has not been operated from 1800 to 2200 Alaska Standard Time, (150° WMT).

In order to produce records that could be more accurately scaled with respect to frequency, the film is run at three times its normal speed, producing the elongated records illustrated in the figures.

The linear frequency-sweep cam, supplied with the equipment, was used with frequency marks at the integral frequencies in megacycles.

APPENDIX IV

The antenna system consisted of two sloping V's with a 55° apex angle and 300 foot legs. Each leg is terminated in a resistance of approximately 300 ohms. The antennas are beamed at 17° geographic bearing, which is roughly half way between geographic and geomagnetic norths.

The antenna pattern was measured by installing a horizontally polarized transmitter in an airplane and then flying along the major axis of the antenna. The AVC voltage from a Collins 51J-4 was recorded and scaled to obtain the pattern. In this way patterns were obtained for 9, 12, 18 and 24 Mc/s. The major lobe of the antennas increased in zenith angle with the frequency. At 9 megacycles the center of the main lobe was approximately 70° from the vertical while at 24 megacycles it was approximately 80° . There were many higher side lobes however, so the probability of energy being transmitted in a given angular band at a given frequency was good.

When the terminating resistors were used the front to back ratio was approximately 10 db, while with the resistors removed it was approximately unity.

Because the polarization of the antenna system was horizontal, there was no practical way of measuring the azimuthal beamwidth.

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